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Interactions of age and leg muscle fatigue on unobstructed walking and obstacle crossing



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ABSTRACT

Older adults commonly report muscle fatigue, which may be associated with reduced walking ability. Elderly may have insufficient awareness of the balance threat caused by muscle fatigue. The aim of this study was to analyze the interaction effects of aging and leg muscle fatigue on gait parameters in walking and obstacle crossing. One hundred and twenty men, who were divided in six groups according to their age (20–29 years, 30–39 years, 40–49 years, 50–59 years, 60–69 years, above 70 years), participated in this study. Participants performed three trials of unobstructed level ground walking and obstacle crossing during walking before and after quadriceps muscle fatigue. To induce fatigue, participants performed a repeated sit-to-stand task from a chair with arms across the chest to a pre-determined cadence (30 cycles/min) using a metronome. Spatial-temporal gait parameters (stride length, duration, and speed, step width, and trailing and leading heel-clearance) were analyzed, and compared by two-way ANOVA (group and fatigue). The results confirmed our hypothesis, showing age-related effects of leg muscles fatigue in both gait conditions. From 40 years old, participants modulated spatial-temporal and vertical impulses in both tasks more in response to fatigue than younger participants, apparently to improve balance and safety. Leg muscle fatigue caused age-dependent changes in both unobstructed level ground walking and obstacle crossing during walking, which appeared to reflect an attempt to maintain balance and safety, probably to counteract adverse fatigue effects.

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1. Introduction

Older adults generally walk more cautiously than young adults, with higher cadence [1,2] and double support time [2,3], and lower gait speed [2,3] and stride length [1]. Additionally, when crossing obstacles, older adults adopt a conservative strategy, which is characterized again by decreased speed and step length [4] in the step crossing the obstacle. While these changes in strategy appear to be aimed at facilitating balance control, they may be less effective in more complex tasks. For example, a shorter step length while negotiating an obstacle may lead to an increased likelihood of the foot contacting the obstacle, leading to a trip or fall. Indeed, elderly show a higher incidence of stumbles and falls than young

adults [5] and specifically in more complex locomotor tasks such as obstacle crossing during walking [6].

The increased fall risk with aging is considered a consequence of a decline in information processing [7], executive function [8], and functional capacity [7,9]. Specifically, it is well documented that muscle strength varies with age [10,11], with increases up to age 20–29 years, a plateau between 30 and 49 years, and a decrease beyond 50 years [12]. However, how and when gait impairments arise due to such aging effects is largely unknown.

Older adults commonly report muscle fatigue [13], possibly due to the relatively high levels of muscular effort that they need to invest in locomotion [14]. Muscle fatigue in turn has been shown to affect the gait pattern [15–20] possibly due to reduced balance control [18,19]. The effects of leg muscle fatigue on walking of older adults were addressed in previous studies [17,18,20]. However, to our knowledge, only Granacher et al. [17] have investigated effects of age and leg muscle fatigue and their interaction on gait. They found that young adults decreased gait speed and stride length in walking under single-task conditions when fatigued, while older adults did not show any changes. In

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dual-task conditions, older adults even increased gait speed and stride length when fatigued. It was suggested that the gait changes observed in young adults reflected an adaptation to deal with impaired balance control, while the older adults may have been insufficiently aware of the balance threat caused by muscle fatigue.

The aim of this study was to analyze the impact of age and leg muscle fatigue on gait parameters while unobstructed level ground walking and in obstacle crossing during walking. We hypothesized that interaction effects of age and leg muscle fatigue would occur in unobstructed level ground and in obstacle crossing. We expected that gait changes with fatigue would reflect a more cautious gait pattern and specifically hypothesized shorter stride length and lower speed and a larger step width in unobstructed ground level walking and obstacle crossing walking, and a higher heel-clearance during obstacle crossing. Moreover, we hypothesized that these changes on gait would be less pronounced in individuals over 50 years of age than in younger groups. To test our hypothesis, we compared the gait of individuals of different ages, in a cross-sectional design, before and after inducing leg muscle fatigue.

2. Material and methods

2.1. Participants

Over two hundred individuals were invited to participate in the study. One hundred and twenty individuals were included. Exclusion criteria were factors that could interfere with gait (such as using an assistive devices), diabetes, medication use, presence of lower limb musculoskeletal, neuromuscular or cardio-respiratory diseases and balance and vision disorders. The participants were distributed over six groups of 20 individuals, according to their age (Fig. 1). The study was approved by the local Ethics Committee (#2055/2008). After agreeing to be enrolled in this study, participants were instructed not to perform any strenuous physical activity 48 h before evaluation. Before the experiment, the participants performed a warming-up of 5 min.

2.2. Maximum voluntary contraction protocol

Maximum voluntary isometric contractions were performed in a leg press device [15,16]. A load cell with a precision of 0.98 N was used in combination with a signal amplifier (EMG System do Brasil Ltda.). The participant performed the test with both legs, with the instruction to produce maximum force as fast as possible. Total contraction duration was 5 s. Two attempts were made with 2 min rest between attempts before and after muscle fatigue. The maximum voluntary contraction was used to confirm the presence of muscle fatigue [21].

2.3. Gait trials

Participants performed three trials of barefoot unobstructed ground level walking and obstacle crossing during walking. The order of trials was randomized for each participant. The instruction given to the participant was to walk over an 8 m wooden pathway, which was covered with a black rubber carpet (3 mm thick), at self-selected speed. For the obstacle crossing trials, the participant was instructed to avoid an obstacle (15 cm high, 80 cm wide and 2 cm thick), which was positioned between two force platforms, midway down the pathway. The starting point of each gait trial was adjusted to ensure that the obstacle was crossed with the right leg and that at least two strides were completed prior to obstacle crossing.

Acquisition of kinematic gait parameters was accomplished with a three-dimensional optoelectronic system (OPTOTRAK Certus), positioned in the right sagittal plane, using a sampling rate of 100 samples/s. Four infrared emitters were placed over the following anatomical points: lateral aspect of calcaneus and head of the fifth metatarsus of the right limb, and medial aspect of calcaneus and head of the first metatarsus of the left limb.

2.4. Muscle fatigue protocol

To induce leg muscle fatigue, participants performed a repeated sit-to-stand task from a chair with arms across the chest. Sit-to-stand movements were performed at a pre-determined cadence (30 cycles/min), using a metronome [15,16]. A standard chair (43 cm in height, 41 cm in width, 42 cm in depth) without arm rests was used for all participants. The fatigue protocol was stopped when the participant indicated that he was unable to continue, when the movement frequency fell below and remained below 30 cycles/min after encouragement, or after 30 min. Immediately after the fatigue protocol, the participant performed the gait trials and the maximal voluntary contractions once again. The time between the fatigue protocol and the gait trials (<3 min) was expected not to allow full recovery [19]. The rate of perceived exertion was measured by the Borg Scale [22] at the beginning and the end of the muscle fatigue protocol. Finally, the endurance time during the fatigue protocol was recorded.

2.5. Data analysis

The mid-pathway stride was analyzed for unobstructed ground level walking. In this stride, we determined stride length, duration, and speed (step length divided by step duration), and step width. For obstacle crossing trials, the crossing step (the step with which the individual crossed the obstacle) was analyzed. The step parameters (length, duration, speed and width), and trailing and leading heel-clearance (vertical distance between the infrared

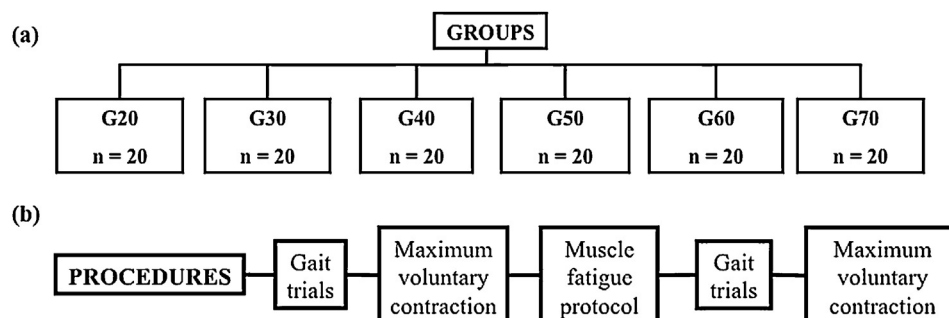


Fig. 1. (a) Group distribution. (b) Protocols sequence of the experiment.

emitter on calcaneus and obstacle) were calculated. Finally, the maximum force in the maximum voluntary contractions was determined.

All the data were digitally filtered using zero-lag Butterworth filters. Kinematic data were filtered with a 5th order low-pass filter with cutoff frequency of 6 Hz. To verify similarity among groups, the anthropometric characteristics, endurance time and final rate of perceived exertion were compared through an ANOVA with age group as the only factor (G20, G30, G40, G50, G60 and G70). Besides, the maximum voluntary contraction was compared before and after fatigue for each group by Student's *t*-tests to confirm leg muscle fatigue. The spatial-temporal of unobstructed ground level walking and obstacle crossing during walking, and maximum isometric force were compared using a two-way ANOVA, with group and fatigue (without and with leg muscle fatigue), with repeated measures over the last factor. When the ANOVA pointed out significant interactions, Tukey univariate tests were carried out. We performed three ANOVAs, one for unobstructed ground level walking, one for obstacle crossing during walking, and one for maximum isometric force.

3. Results

The characteristics of each group are presented in Table 1. The groups had similar body mass, but the G70 individuals were shorter than all other groups ($p < 0.01$).

The fatigue protocol did induce fatigue in all groups as demonstrated by the lower values of maximum voluntary forces ($p < 0.05$) with G50 group showing a larger reduction (25.7% versus 11.6% on average in the other groups) (Table 1). Moreover, all groups reported an almost maximum rate of perceived exertion at the end of the protocol. The final rate of perceived exertion was not different between groups ($p > 0.07$). However, there was a difference in endurance times between groups ($p < 0.05$). Values for the G20 group were higher than for the G70, and values for the G30 group were higher than for the G60 and G70 groups.

3.1. Unobstructed ground level walking

Univariate analyses indicated main effects of group and fatigue (Table 2). Moreover, there were group*fatigue interactions for stride length, stride duration, and stride velocity. For group factor, the G70 group showed shorter stride length than all other groups, and lower stride speed than the G40 group. In addition, the G60 and G70 groups walked with smaller step width than younger groups. For the main effects of fatigue, participants in all groups walked with larger stride length and step width, lower stride duration, and higher stride speed, with leg muscle fatigue.

Regarding the group*fatigue interactions (Fig. 1), the Tukey univariate test indicated that the groups over 40 years old (G40, G50, G60 and G70) significantly increased stride length with leg muscle fatigue ($p < 0.05$), while the younger groups (G20 and G30) did not show an effect of muscle fatigue ($p > 0.05$). All groups reduced stride duration with muscle fatigue ($p < 0.05$), but the oldest group (G70) decreased stride duration significantly more in

comparison to G20, G30 and G40 groups. Finally, all groups increased stride speed with muscle fatigue ($p < 0.05$), but the groups over 50 years old (G50, G60 and G70) showed a larger increase of stride speed in comparison to the youngest (G20, G30 and G40) groups.

3.2. Obstacle crossing during walking

Univariate analyses indicated main effects of group and fatigue (Table 2). Moreover, there were group*fatigue interactions for step duration, and trailing and leading heel-clearance. For group factor, the G50 group walked with larger step length than the G70 group. The G60 group walked with smaller step width than the G40 and G70 groups. For the main effects of fatigue, participants in all groups walked with larger step width and leading heel-clearance, shorter stride duration, and higher step speed after leg muscle fatigue.

Group*fatigue interactions (Fig. 2) showed that while all groups decreased the duration of the crossing step with fatigue ($p < 0.05$), a greater reduction was seen in the G40, G60 and G70 groups, such that pre-fatigue differences between the groups disappeared ($p > 0.05$). For leading limb heel-clearance, no clear age-related pattern was observed: the G20, G30, G60 and G70 groups did not change clearance with fatigue, while the G40 and G50 groups increased clearance ($p < 0.05$). For trailing limb heel-clearance, also no clear age-related pattern was observed: no group changed the clearance after muscle fatigue ($p > 0.05$), but the G70 group showed less clearance than G20, G30, G40 and G50 groups only after muscle fatigue ($p < 0.05$).

4. Discussion

The main finding of this paper was that effects of leg muscles fatigue in unobstructed ground level walking and obstacle crossing during walking are age dependent. However, in line with our hypothesis, for most of the variables studied, changes with fatigue were more pronounced in the participants above 50 years old (G50, G60 and G70), but in fact many of these changes were already found from 40 years old (i.e. in G40 as well). In the following paragraphs, we will discuss explanations of the interaction effects of age and leg muscle fatigue and offer interpretations in terms of adverse effects of leg muscle fatigue versus the adaptive role in dealing with the fatigue.

4.1. Unobstructed ground level walking

For all spatial-temporal gait variables, except step width, changes with fatigue were more pronounced in the elderly. Stride length increased with fatigue and more so among the older groups. An increase in stride length is unlikely to be a direct effect of fatigue, since probably more muscle force is required to take bigger strides. It could be that participants chose to increase stride length, to enhance balance control in the sagittal plane. In walking, the anterior margin of safety is negative, i.e. the extrapolated center of mass (a function of the position and speed of the center of mass) is

Table 1

Subject characteristics, endurance time, rating of perceived exertion (RPE) and maximum isometric force before and after leg muscle fatigue for each group.

Variables		G20	G30	G40	G50	G60	G70
Age (years)		24.00 ± 2.88	32.5 ± 2.74	44.00 ± 2.98	54.5 ± 3.25	64.00 ± 2.68	74.50 ± 4.50
Weight (kg)		77.96 ± 14.74	79.26 ± 14.23	84.63 ± 15.51	82.17 ± 13.40	77.99 ± 12.61	73.00 ± 12.26
Height (m)		1.78 ± 0.04	1.74 ± 0.06	1.75 ± 0.06	1.71 ± 0.07	1.71 ± 0.06	1.65 ± 0.06
Endurance time (min)		12.00 ± 10.50	12.90 ± 11.00	8.60 ± 9.80	6.50 ± 7.00	4.8 ± 3.43	3.00 ± 2.49
RPE (maximum = 20)		19.15 ± 1.14	18.70 ± 1.42	18.60 ± 1.31	18.65 ± 3.08	18.60 ± 1.60	17.39 ± 1.61
Maximum voluntary contraction (N)	Before fatigue	3269.28 ± 1170.72	4012.97 ± 1014.06	3610.14 ± 685.43	3009.34 ± 1078.21	2420.07 ± 929.41	2765.02 ± 935.44
	After fatigue	2878.65 ± 1194.63	3320.91 ± 896.55	3293.85 ± 532.45	2235.28 ± 818.39	2223.84 ± 633.16	2433.96 ± 711.76

Table 2

Means and standard deviations of spatial-temporal in level gait and obstacle crossing by group without and with muscle fatigue. For each variable, the first line is without leg muscle fatigue and the second line is with leg muscle fatigue. The last three columns show the *p*-values for main effects of group and fatigue and for the group*fatigue interaction, respectively.

Variables	G20	G30	G40	G50	G60	G70	Group	Fatigue	Group* fatigue
Level gait									
Stride length (cm)	135.67 ± 11.71	134.25 ± 10.19	131.00 ± 8.20	137.07 ± 13.93	135.35 ± 13.10	124.18 ± 13.49	0.001	0.001	0.001
	136.15 ± 12.05	134.62 ± 12.25	133.97 ± 7.70	138.97 ± 14.57	139.55 ± 12.70	128.62 ± 15.41			
Step width (cm)	11.48 ± 2.70	11.42 ± 2.42	12.85 ± 3.59	11.80 ± 2.87	9.97 ± 2.60	10.22 ± 2.50	0.001	0.001	0.9
	12.73 ± 3.06	12.78 ± 2.69	14.06 ± 2.99	13.01 ± 3.30	10.96 ± 2.71	11.10 ± 2.67			
Stride duration (s)	1.09 ± 0.10	1.11 ± 0.24	1.10 ± 0.09	1.07 ± 0.07	1.10 ± 0.08	1.08 ± 0.11	0.58	0.001	0.001
	1.07 ± 0.08	1.09 ± 0.25	1.06 ± 0.09	1.05 ± 0.08	1.06 ± 0.07	1.04 ± 0.11			
Stride speed (cm/s)	125.73 ± 17.32	125.28 ± 21.12	120.12 ± 13.66	128.95 ± 18.25	124.00 ± 17.34	116.79 ± 19.63	0.02	0.001	0.001
	128.70 ± 17.68	128.88 ± 24.25	127.38 ± 14.66	136.62 ± 19.66	133.30 ± 18.06	126.2 ± 5.29			
Crossing obstacle									
Step length (cm)	71.68 ± 8.45	71.90 ± 7.78	70.30 ± 7.36	72.41 ± 7.66	69.89 ± 7.48	68.47 ± 9.06	0.03	0.08	0.51
	72.79 ± 7.52	71.29 ± 7.37	70.88 ± 7.38	73.53 ± 8.75	70.03 ± 9.13	69.13 ± 9.01			
Step width (cm)	10.58 ± 3.30	10.39 ± 3.77	12.52 ± 4.13	10.35 ± 4.05	9.61 ± 5.09	12.33 ± 5.09	0.001	0.001	0.41
	12.81 ± 3.69	12.34 ± 4.03	13.95 ± 4.82	12.01 ± 4.32	10.88 ± 5.07	13.02 ± 5.27			
Step duration (s)	0.63 ± 0.10	0.61 ± 0.06	0.65 ± 0.05	0.60 ± 0.08	0.65 ± 0.07	0.65 ± 0.08	0.17	0.001	0.006
	0.61 ± 0.09	0.60 ± 0.07	0.61 ± 0.06	0.59 ± 0.09	0.62 ± 0.11	0.60 ± 0.09			
Step speed (cm/s)	117.66 ± 29.78	120.52 ± 21.33	110.00 ± 15.38	121.97 ± 21.50	109.85 ± 17.97	108.73 ± 24.34	0.06	0.001	0.33
	124.66 ± 54.92	121.11 ± 20.23	118.13 ± 18.47	123.90 ± 21.69	115.94 ± 23.51	116.93 ± 25.36			
Trailing heel-clearance (cm)	31.15 ± 5.62	30.51 ± 6.97	29.32 ± 7.65	28.06 ± 4.73	29.34 ± 6.59	26.93 ± 7.16	0.06	0.78	0.01
	30.16 ± 5.11	29.93 ± 6.66	29.62 ± 7.21	29.64 ± 5.45	28.57 ± 7.39	27.82 ± 7.29			
Leading heel-clearance (cm)	9.05 ± 3.36	9.71 ± 4.14	9.90 ± 4.13	10.03 ± 4.46	8.75 ± 4.24	9.91 ± 3.65	0.16	0.001	0.005
	9.38 ± 3.20	9.38 ± 4.71	11.11 ± 4.63	11.36 ± 5.18	9.61 ± 4.69	9.88 ± 3.93			

in anterior to the base of support, which would cause a forward fall if the base of support is not moved forward by taking a step [23]. Increasing step length may decrease the magnitude of the negative margin, making it easier to come to a stop in a single step and in principle making it easier to avoid a forward fall [24]. However, in

experiments in which balance was externally perturbed by means of lateral translations of a treadmill, subjects shortened steps presumably to increase the backward margin of safety at the expense of the forward margin of safety [25]. Obviously, the perturbations of balance control are different between these

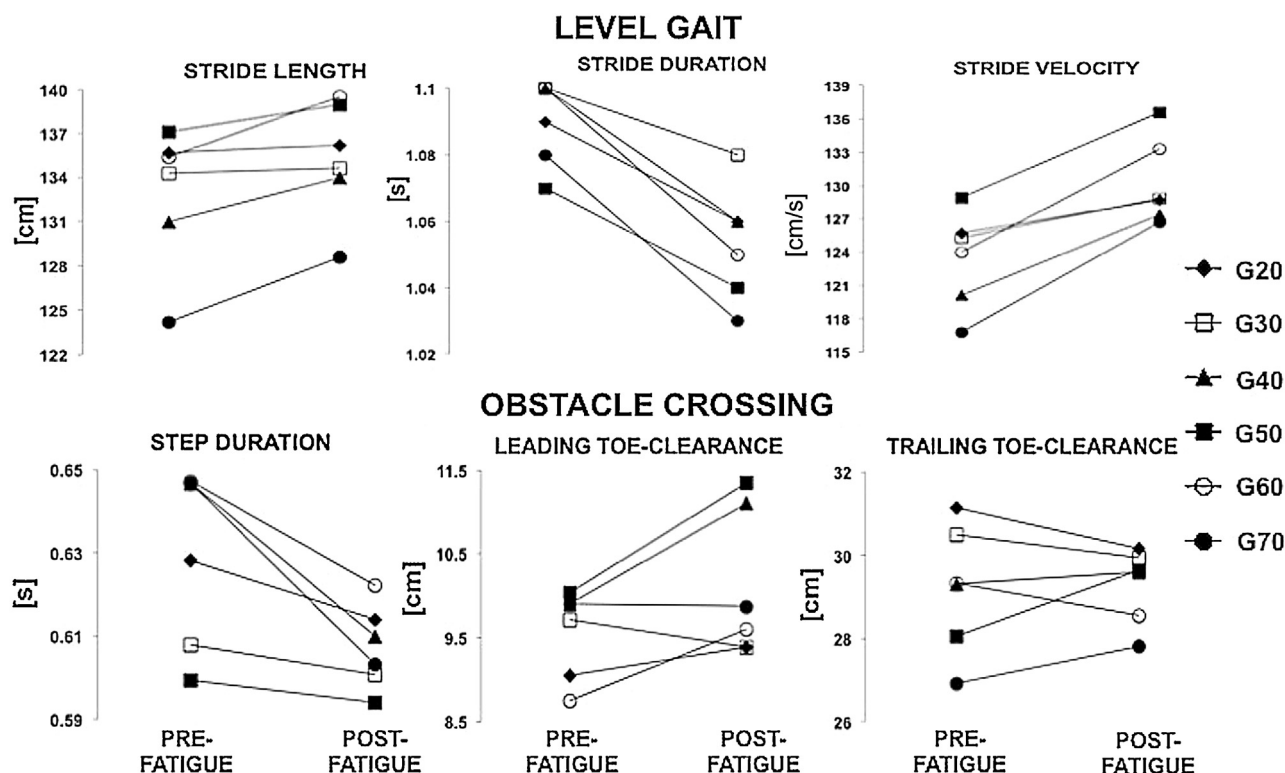


Fig. 2. Group*fatigue interaction for spatial-temporal parameters of unobstructed ground level walking (first line) and obstacle crossing during walking (second line).

experiments, but it is at present unclear why either the forward or backward margin of safety would be prioritized in these conditions.

Stride duration decreased with fatigue and again more so among the older groups. Again this is unlikely to be a direct effect of fatigue. A decrease in stride time has been observed under external perturbations of balance [25] and facilitates balance control in the medio-lateral direction as well as in the fore-aft direction [24]. Reduced stride duration may also relate to participants choosing to shorten the unstable phases of the gait cycle (e.g. single leg support times). Moreover, step width increased with fatigue in a similar manner across age groups. An increase in step width with fatigue has been reported previously [18] and is generally interpreted as facilitating balance control in the medio-lateral direction [18,25].

The increase stride length and decreased stride duration caused an increase in gait speed, which, as the changes in the underlying variables, was more pronounced in the older groups. Granacher et al. [17] reported a similar increase in stride length and gait speed with fatigue in older adults. It is often assumed that increased gait speed is associated with an increased risk of falls [17]. However, it appears that changes in stride length and duration are more important in terms of balance control than the resulting gait speed [25] and stability of the gait pattern may actually be improved with higher gait speed [26]. On the other hand participants may have tried to perform the task as quickly as possible [16,17] to return to a position of greater stability as soon as possible.

4.2. Obstacle crossing during walking

As in unobstructed ground level walking, with fatigue, participants increased step width and decreased step duration in obstacle crossing during walking. In line with the above, these changes might be interpreted as compensatory changes to facilitate balance control. Similar to unobstructed level ground walking this coincided with an increased gait speed and a tendency toward an increase in step length. The latter findings appears to be in contrast with previous studies on obstacle crossing in which it was found that step length and gait speed decreased in the presence of a postural threat [27]. This suggests that the present findings cannot simply be interpreted as the consequence of an increase in postural threat experienced due to leg muscle fatigue, but are more specific to the fatigue experienced by the individual during the experiment.

Leading foot heel-clearance increased in the older groups, but not in the younger groups. High heel-clearance maybe used to avoid obstacle contact [28], in spite of a higher energy demand [29]. The exception here was the oldest group (over 70 years), which also showed no increase in clearance. Hatton et al. [20] also did not find increase of leading foot heel-clearance in individuals over 70 years old. Differences in fatigue protocols with this previous study may account for this disparity. Our fatigue protocol was designed to simulate daily activities with a moderate intensity, while Hatton used maximum cadence sit-to-stand movements, which can be sustained for a shorter period, due to which fatigue levels may have been lower.

Strikingly trailing heel-clearance increased in the oldest group only. It could be that strength decrements that occur from the fifth decade at a rate of approximately 12–15% per decade [30], in combination with leg muscle fatigue limits the step of the leading leg in this group directly. On the other hand, when individuals cross an obstacle with their trailing limb, they do not have visual feedback on clearance, in contrast with the crossing of the leading limb. Therefore, perhaps the older adults compensated clearance of the trailing limb more, to avoid stumbling with their trailing limb.

4.3. Limitations and conclusion

Effects of age were studied in a cross-sectional design. However, an alternative longitudinal study would need more than 50 years and appears not feasible. The participants over 70 years old were on average shorter than the other groups. However, an analysis on spatial parameters normalized by height yielded similar results. Moreover, only men were analyzed and we did not consider their habitual level of physical activity. Generalization of the results should therefore be done with care. Although the fatigue protocol was designed to induce fatigue predominantly in the quadriceps muscles, it is important to consider that other leg muscles are involved and may have been fatigued as well. Moreover, fatigue other leg muscles, e.g. ankle muscles (triceps surae muscle) might have other (more pronounced) effects [17].

In conclusion, leg muscle fatigue caused age-dependent changes in both unobstructed ground level walking and obstacle crossing during walking. In general, spatial-temporal gait parameters were changed in a way that reflects that individuals were seeking balance and safety to counteract adverse fatigue effects. The adjustments in gait with fatigue in both tasks were more pronounced in participants over 40 years old than in younger individuals.

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Conflict of interest

None declared.

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